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A review on electrical motors energy use and energy savings

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ABSTRACT

The industrial sector is the largest users of energy around the world. Industrial motor uses a major fraction of total industrial energy uses. This paper describes a comprehensive literature review about electric motor energy analysis. This paper compiles latest literatures in terms of thesis (MS and PhD), journal articles, conference proceedings, web materials, reports, books, handbooks on electrical motor energy use, losses, efficiency, energy savings strategies. Different types of losses that occur in a motor have been identified and ways to overcome these losses explained. An energy audit that helps to identify motor energy wastages have been discussed extensively. As motors are the major energy users, different energy savings strategies such as use of high-efficient motor, variable speed drive (VSD), and capacitor bank to improve the power factor to reduce their energy uses have reviewed. Different policy measures (i.e. regulatory, voluntary and incentives based) to save motor energy use have been reviewed and presented in this paper. In this review, computer tools that can be used to analyze electric motors energy used has been discussed. Cost parameters to carry out economic analysis have been shown as well. Moreover, payback period for different energy savings strategies have been identified.

Contents

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1. Introduction

Electric motors have broad applications in such areas as industry, business, public service and household electrical appliances, powering a variety of equipment including wind blowers, water pumps, compressors and machine tools. In industrially developed nations and large developing nations, electric motors account for a considerable proportion of total national power consumption. Statistics indicate that electric motors are generally responsible for about 2/3 of industrial power consumption in each nation, or about 40% of overall power consumption [1]. According to estimates, adopting existing well-established energy-conserving technologies and products would result in savings of approximately 11–18% [1].

Recently, there has been a growing concern about energy use and its adverse impact on the environment. Most of the developing countries shifted from agriculture towards industrialization and urbanizations due to the economic growth since the last few decades. The growth in the industrial sector, promising a healthy growth of gross domestic products (GDP), severely affected the ability to maintain the fuel supply or reserve. Introducing the concept of rational use of energy aims at reducing energy use and also corresponds to the optimum use of all limited economic resources [22]. This definition indicates that the measures leading to a more rational use of energy showed the advantages over the actual current situation. Energy losses in a large number of industries exist, and there is potential for energy-efficiency improvements [23]. Among the various sectors contributing to greenhouse gas (GHG) emissions, the contribution of the industrial sector was significant. Thus, mitigating GHG emissions from the industrial sector offers the best means of reducing overall GHG emissions. Therefore, energy conservation means less reliance on energy imports and, thus, less GHG emissions. Previous studies have reported that implementing a few options with little or no cost in the industrial sector could reduce 10–30% of GHG emissions [24,25].

It can be achieved either by reducing total energy use or by increasing the production rate per unit of energy used. On the other hand, improving energy efficiency is the key to reducing GHG emissions. Therefore, energy research organizations and government are actively engaged in developing methods of assessing energy efficiency. This assessment can provide a base for establishing energy policy and can simultaneously reduce GHG emissions. One of the ways to attain the more-efficient use of final energy in an industry is to determine the amount of energy used and energy losses. Various types of equipment and devices that use energy at varying levels of efficiency depend on the characteristics and working conditions [26–30]. Energy use performances and energy efficiencies of the industry have also been studied in different surveys [31–33] in many countries. In Slovenia, industrial sector uses about 52% of total electrical energy [14]. In Turkey about 35% of total energy is used in industrial sector [34]. Approximately half of UK's generated electricity is used to drive electrical motors. This means that efficiency improvements to electrical machines can have a very large impact on energy use [6]. Motor-driven systems account for approximately 65% of the electricity used by EU industry [35]. In Jordan, industrial sector uses about 31% of total energy [10]. In Malaysia, about 48% of total industrial energy used by industrial motors as can be seen in Table 1 [11,12]. In many industrialized countries, more than 70% of the total produced energy is used by electric motors. Table 1 shows the electrical motor energy consumption for some selected countries. Fig. 1 shows the

Table 1
Electrical motor energy uses for selected countries.

Country	Motor energy use (%)	Reference
US	75	[3–5]
UK	50	[6]
EU	65	[2,7–9]
Jordan	31	[10]
Malaysia	48	[11,12]
Turkey	65	[13]
Slovenia	52	[14]
Canada	80	[15]
India	70	[16]
China	60	[17]
Korea	40	[18]
Brazil	49	[19]
Australia	30	[20]
South Africa	60	[21]

breakdown of motor uses in an industry. Therefore, the cost of energy to operate motors has become a real concern for industries. On the other hand, the concern for the environment particularly through the emission of green-house gases and other pollutants has prompted the regulators of utilities to enforce alternative measures to meet load growth, instead of building additional power stations [36]. Comprehensive literatures in energy electrical motors' energy savings, policy, and technology can be found in a handbook written by Nadel et al. [37]. The energy that electric motors used in plants is about 65% of the total energy consumption in Turkey. Therefore, it is important to choose "high-efficiency" motors in plants [13].

There are a number of different terms used to describe the AC drive. AFD, VSD, VFD and inverters all are used but have the same meaning. The main purpose for all AC drives is to control the operation of the AC motor with regard to speed and torque. A drive is a technology that controls a motor's speed to correspond with its load requirements. VSDs have been used to provide significant savings in a number of applications. These include:

- Variable air volume (VAV) in air conditioning systems.
- Chilled water pumping (e.g. secondary chilled water pumps).
- Exhaust air systems (e.g. dust extraction, paint shop exhaust)

By introducing variable speed to the driven load, it is possible to optimize the efficiency of the entire system, and it is in this area that the greatest efficiency gains are possible [6].

Power factor correction equipment that can be applied at the motor level will not only decrease energy use but will significantly extend the life of the equipment. Additionally, it also maximizes the capacity of the power system, improves the quality of voltage, and reduces the power losses. In order to decrease the cost and to improve the efficiency, the reactive power drawn from the line has to be reduced by supplying it from other reactive power source.

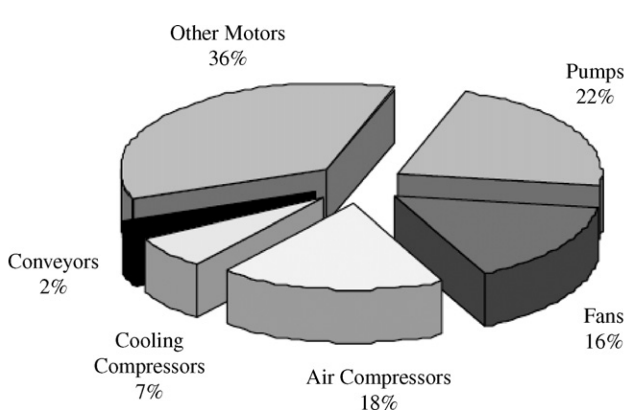

Fig. 1. Share of motor energy use by type of end-use, in the industrial sector in EU [2].

Capacitors and synchronous motors have been mostly used to compensate the reactive power in many applications [38,39]. Capacitors today are smaller and can be applied more easily at the motor level than a few years ago. They have also come down in price to a level where the return on investment (ROI) is usually less than 1 year making them a fast return on the money spent. The capacitors have a life of over 20 years so the savings are realized for decades. By combining several of the solutions, aggregate energy savings can easily approach 30–35% [40].

It may be mentioned that to the best of author's knowledge there is no comprehensive review about motor energy use, savings, and economic analysis in the literatures. It is expected that this study will fill that gaps by providing comprehensive literatures in terms of thesis (MS and PhD), journal articles, conference proceedings, web materials, reports, books, handbooks on electrical motor energy use, losses, efficiency, energy savings strategies.

Author hopes that this study will be useful for policy measures for global industrial motors energy use. Furthermore, the study could provide important guidelines and insights for future research and development allocations and energy projects to reduce motors energy use. It will create awareness among the industrial energy users to reduce the motor energy uses along with environmental pollution reduction.

2. Motor losses

Based on these references it has been found that the following losses occur in induction motors [41]. The efficiency of a motor is determined by intrinsic losses that can be reduced only by changes in motor design. Intrinsic losses are of two types: *fixed losses*, and *variable losses*.

2.1. Fixed losses

Fixed losses independent of motor load consist of magnetic core losses and friction and windage losses. Magnetic core losses (sometimes called iron losses) consist of eddy current and hysteresis losses in the stator. They vary with the core material and geometry and with input voltage. Friction and windage losses are caused by friction in the bearings of the motor and aerodynamic losses associated with the ventilation fan and other rotating parts.

2.2. Variable losses

Variable losses dependent on load consist of resistance losses in the stator and in the rotor and miscellaneous stray losses. Resistances to current flow in the stator and rotor result in heat generation that is proportional to the resistance of the material and the square of the current (I^2R). Stray losses arise from a variety of sources and are difficult to either measure directly or to calculate, but are generally proportional to the square of the rotor current [42].

A motor's function is to convert electrical energy to mechanical energy to perform useful work. Even though standard motors operate efficiently, with typical efficiencies ranging between 83% and 92%, energy-efficient motors perform significantly better. An efficiency gain from only 92% to 94% results in a 25% reduction in losses. Since motor losses result in heat rejected into the atmosphere, reducing losses can significantly reduce cooling loads on an industrial facility's air conditioning system. Motor energy losses can be segregated into five major areas, each of which is influenced by design and constructions [43–49].

2.3. Core loss

Core loss represents energy required to magnetize the core material (hysteresis) and includes losses due to creation of eddy

currents that flow in the core. Core losses are those found in the stator-rotor magnetic steel and are due to hysteresis effect and eddy current effect during magnetization of the core material. These losses are independent of load and account for 20–25% of the total losses. The hysteresis losses are a function of flux density. Eddy current losses are generated by circulating current within the core steel laminations.

2.4. Windage and friction

Windage and friction losses occur due to bearing friction and air resistance. Both core losses and windage and friction losses are independent of motor load. Friction and windage losses result from bearing friction, windage and circulating air through the motor and account for 8–12% of total losses. The reduction in heat generated by stator and rotor losses permits the use of smaller fan.

2.5. Stator losses

Stator losses appear as heating due to current flow (I) through the resistance (R) of the stator winding. This is commonly referred to as an I^2R loss. These losses are major losses and typically account for 55–60% of the total losses. I^2R losses are heating losses resulting from current passing through stator and rotor conductors. I^2R losses are the function of a conductor resistance, the square of current. Resistance of conductor is a function of conductor material, length and cross sectional area. This involves lowering the operating flux density and possible shortening of air gap. Rotor I^2R losses are a function of the rotor conductors (usually aluminium) and the rotor slip.

2.6. Rotor losses

Rotor losses appear as I^2R heating in the rotor winding. Rotor losses can be reduced by increasing the size of the conductive bars and end rings to produce lower rotor losses, another form of power losses, are also called slip losses because they are largely-but not entirely-dependent on the degree of slip the motor displays. Slip is the difference in rpm between the rotational speed of the magnetic field and the actual rpm of the rotor and shaft at a given load.

2.7. Stray load losses

Stray load losses are the result of leakage fluxes (I) through the resistance (R) of the stator winding and appear only when the motor is operating at under load. These losses vary according to square of the load current and are caused by leakage flux induced by load currents in the laminations and account for 4–5% of total losses.

This is commonly referred to as an I^2R loss. Both stray load losses and stator and rotor I^2R losses increase with motor load. Loss distributions as a function of motor horsepower are given in Table 2. Amount of losses that take place in motors are shown in Figs. 2 and 3.

Table 2
Typical losses at different motor power [43].

Types of loss	Motor horsepower 25	Motor horsepower 50	Motor horsepower 100
Stator	42	38	28
Rotor	21	22	18
Core losses	15	20	13
Windage and friction	7	8	14
Stray load	15	12	27

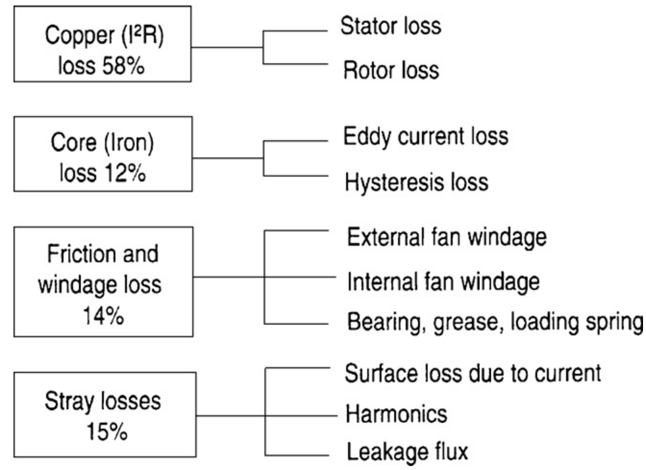

Fig. 2. Losses in a typical motor [44,50,51].

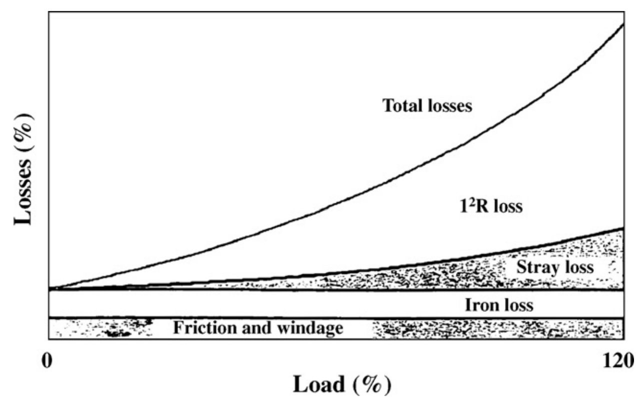

Fig. 3. Motor losses with load.*Source*: [52–54].

2.8. Ways to reduce a motor losses

The only way to improve motor efficiency is to reduce motor losses. Since motor losses produce heat, reducing losses not only saves energy directly but can also reduce cooling load on a facility's air conditioning system. Table 3 summarizes the ways of reducing motor losses.

It was reported in reference [56] that losses are determined as per IEEE 112 Method B and results are presented for standard and energy-efficient motors of different capacities in Table 4.

3. Energy audit

A systematic approach, to monitor industrial energy consumption and to pin-point sources of wastage, is known as energy audit. An energy audit study helps an organization to understand and analyze its energy utilization and identify areas where energy use can be [44,47,57,58] reduced, decide on how to budget energy use, plan and practice feasible energy conservation methods that will enhance their energy efficiency, curtail energy wastage and substantially reduce energy costs. The energy input is an essential part of any manufacturing process and often form a significant part of expenditure of the plant.

Any savings in energy directly adds to the profit of the company. The cost of Energy inputs viz. electricity and fuel are increasing and excessive consumption of energy eat up the profits of the company [27].

The energy audit serves to identify all the energy streams in a facility, quantify energy usage, in an attempt to balance the total

Table 3
Ways to minimize motor losses [50,55,51].

Power loss area	Ways to reduce
Stator	Use of more copper and larger conductors increases cross sectional area of stator windings. This lowers the resistance of the windings and reduces losses due to current. I^2R losses can be decreased by modifying the stator slot design or by decreasing insulation thickness to increase the volume of wire in the stator. Motor operation closer to synchronous speed will also reduce rotor I^2R losses.
Rotor	Use of larger motor conductors bars increase the cross section, thereby lowering conductor resistance and losses due to current flow.
Core/iron losses	Use of a thinner gauge because lower loss core steel reduces eddy current losses. Longer core adds more steel to the design, which reduces losses due to lower operating flux densities. Core losses can be reduced through the use of improved permeability electromagnetic (silicon) steel and by lengthening the core to reduce magnetic flux densities. Eddy current losses are decreased by using thinner steel laminations.
Windage and friction	Use of a low loss fan design reduces losses due to air movement. Use of bearing with lower friction.
Stray load	Use of optimized design and strict quality control procedures minimizes stray load losses.

energy input with its use. An energy audit is thus the key to a systematic approach for decision-making in the area of energy management [59]. As a result, the energy audit study becomes an effective tool in defining and pursuing a comprehensive energy management programme. As the focus of the paper is about electric motor energy usage, details of energy audit are also towards electric motor energy management through an energy audit.

Numerous studies have been published on energy audit and energy analysis results for different industries [16,22,26,27,29,60–69].

3.1. Electric motor energy audit objectives [30,44]

Following are the objectives that can be considered for an electric motor energy audit:

- To identify motor energy use in an industry.
- To implement energy savings measures by which individual industry can conserve energy used in their high-energy using equipment/processes such as motors.
- To provide a pathway to benchmark energy usage of electric motors in other industries.
- Identify electric motor energy wastages.

Table 4
Loss comparison of standard and efficient motors.

Power loss to the total loss ratio	Efficiency class	3 kW	7.5 kW	11 kW	15 kW
Core loss (%)	SD	17	17	20	17
	EEM	11	14	15	12
Friction and windage loss (%)	SD	3	4	4	5
	EEM	14	12	14	10
Stator current loss (%)	SD	45	45	42	39
	EEM	40	40	36	37
Rotor current loss (%)	SD	29	22	21	26
	EEM	26	20	22	27
Stray load loss (%)	SD	9	12	13	13
	EEM	6	14	13	14

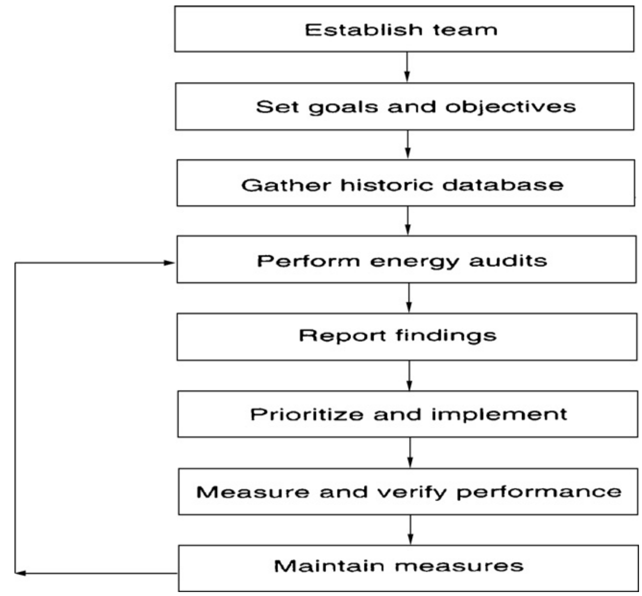

Fig. 4. Typical energy management program [44].

3.2. Energy audit process

Energy management requires a systematic approach-from the formation of a suitable team, to achieving and maintaining energy savings. A typical process is outlined in Fig. 4.

3.3. Benefits of energy audit

Following benefits can be achieved through an electric motor energy audit [44,70]:

- Identifies energy losses for corrective action.
- Impact of operational improvements can be monitored.
- Reduces the specific energy consumption and operating costs (approximately 20–30%) by systematic analysis.
- In addition to the potential dollar savings from an energy audit, the results may lead to environmental benefits such as greenhouse gas reductions, environmental credits as greenhouse gas reductions.
- Improves the overall performance of the total system and the profitability and productivity.
- Averts equipment failure.
- Estimates the financial impact of the energy conservation projects.
- Serves as a very good self-auditating cum correcttion system for performance improvement.

3.4. Types of energy audit

There can be three types of energy audits [44,47].

1. Preliminary audit
2. Single purpose
3. Comprehensive

3.4.1. Preliminary energy audit

Preliminary audit is conducted in a limited span of time. It focuses on major energy supplies and demands of the industry. The scope of this audit is to highlight energy costs and to identify wastages in major equipment processes it sets priorities for optimizing energy consumption. This type of energy audit checks energy use and energy management in factories.

The preliminary audit alternatively called a simple audit, screening audit or walk-through audit, is the simplest and quickest type of audit. It involves minimal interviews with site operating personnel, a brief review of facility utility bills and other operating data, and a walk-through of the facility to become familiar with the building operation and identify glaring areas of energy waste or inefficiency.

Typically, only major problem areas will be uncovered during this type of audit. Corrective measures are briefly described, and quick estimates of implementation cost, potential operating cost savings, and simple payback periods are provided. This level of detail, while not sufficient for reaching a final decision on implementing a proposed measure, is adequate to prioritize energy-efficiency projects and determine the need for a more detailed audit [71].

3.4.2. Targeted energy audit

This type of audit provides a detailed analysis on one or more types of projects. The projects analyzed could result from a preliminary audit or vendor or could be selected by the facility staff as needed to repair or upgrade the project. Examples include those that focus only on electric motor energy managements systems.

3.4.3. Detailed energy audit

This covers estimation of energy input for different processes, losses, collection of past data on production levels and specific energy consumption. It is a comprehensive energy audit action plan to be followed effectively by the industry. The scope of this audit is to formulate a detailed plan on the basis of quantitative and control evaluation, to evolve detailed engineering for options to reduce total energy costs, consumption for the product manufactured. This type of audit covers measuring and collecting the detailed data. Energy audit for planning the further service is also included in details energy audit.

Detailed energy audit: Detailed energy audit is a quantitative assessment of the extent of rational use of energy and aims at deriving recommendations by not only considering available data but also undertaking instrumented measurements and testing of major energy consuming sub-systems which are sensitive to energy cost of the product.

The objective of the detailed energy audit is to the operations of energy intensive equipment/systems for identification of potential areas wherein energy savings are practically feasible [72].

3.5. Tools for energy audit

To conduct a detailed energy audit following tools are needed to get the pertinent data for motor energy use [44,47]:

1. Clamp-on power meter: This type of meter helps measure power consumption, current drawn, load factor and power factor. The meter should have a clamp-on feature to measure current and probes to gauge voltage so that measurements can be recorded without any disruption to normal operation.
2. Portable tachometer: This meter is useful for measuring the speed of the motor. Optical type tachometer is preferable due to the ease of measurement.
3. Thermocouple sensor: Thermometer/thermocouple sensors are useful to measure the temperature of the motor so that level of temperature can be checked whether motor is overheated or not. This will prevent motor failure or damage. Moreover, temperature gain will cause a motor to consume more energy. Knowing temperature allows the auditor to determine motor efficiency. Most commonly used sensors are RTDs and thermistors. The accuracy of these sensors is important. Such temperature sensors need to be connected to a data logger for data storage and analysis.
4. Data logger: Data loggers are used to monitor and log data such as temperatures, motor current, and power. Data loggers are normally portable and can accept different inputs from sensors.

3.6. Data needed for electrical motor energy audit

Following are the most important data that are needed for electrical motor energy analysis [73]:

- load factor
- production figure
- power rating
- power factor
- efficiency at given LF
- efficiency adjusted to that at 75% of LF
- duty factor (hours of operation/year)
- motor load profile
- utility bill
- demand uses
- peak and off peak usage hours

4. The selection of an electric motor in suitable power/motor load factors

It is very important to select an electric motor of suitable power to work efficiently. Motor oversize is one of the most frequently misapplication encountered and difficult to be fixed. Oversizing accounts for a considerable share of the efficiency problems often found in motor applications. According to a US department of energy study, 44% of motors in industrial facilities operate at 40% or less of their full load capacity and are thus, operating inefficiently [74,75]. In general, motors are chosen in big capacities to meet extra load demands. Big capacities cause motors to work inefficiently at low load. Normally, motors are operated more efficiently at 75% of rated load and above. Motors operated lower than 50% of rated load, because they were chosen in big capacity, performing inefficiently, and due to the reactive current increase, power factors are also decreased. These kinds of motors do not consume the energy efficiently because they have been chosen in big power, not according to the needs [44]. These motors should be replaced with new suitable capacities motors, and when purchasing new motors, energy saving motors should be preferred.

Oversized, under-loaded motors should be replaced with smaller premium energy-efficient motors. A motor with a higher horsepower rating than is required by the load operates at part load. Motor efficiency and power factor declines below 50% of full load, increasing utility power factor charges [76].

The motor shows the stated efficiency on the label of the motor when it is fully loaded. The efficiency value in different loads is different from the value that has been showed on its label. Fig. 5 shows the variations of motor efficiencies according to loading. The efficiency at which the motor is being operated is determined by looking at the efficiency loading curve. The efficiency value is equal to the maximum value only when the motor is operated at loading values of 75% and higher. The preferred optimum operating region is between 60% and 90% of the rated load for motors; the ideal value is when the motor is operated in its full load [13].

Only few motors run at anywhere near full load as mentioned by Capehart et al. [47], based on their energy audit experiences.

A common assumption made by many energy auditors and analysts is that motor load factors are around 80%. This value is rarely seen in motors in industrial facilities. In most of the applications, motors experience variable loads that average well below 80%. Authors also mentioned that 75% of all motors have load factors less than 60%. One of the Authors of Capehart et al. [47]

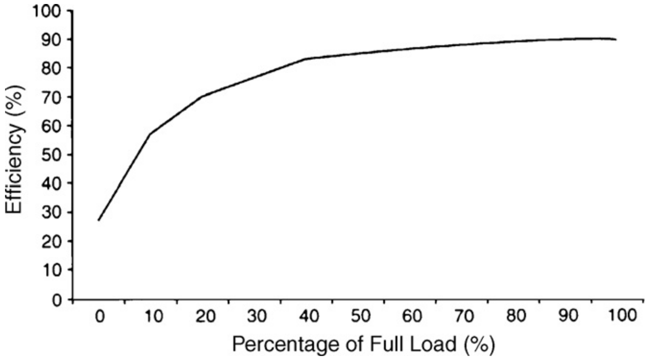

Fig. 5. Relationship between motor loading and efficiency [48].

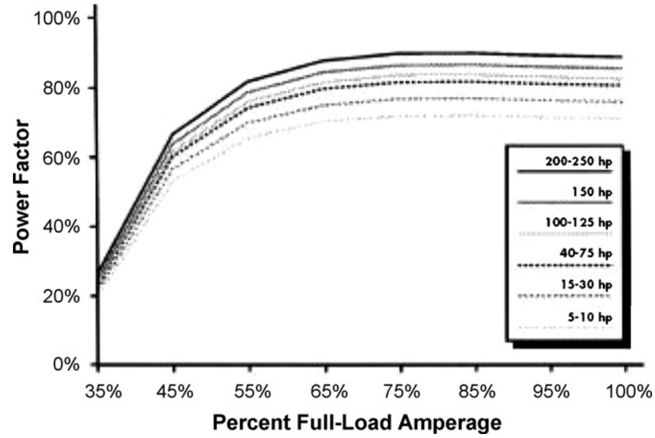

Fig. 6. Motor power factor as a function of % full load.

performed over 100 audits of medium-sized manufacturing companies, and the average motor load factors have ranged from about 30–40%. Normally, the load factor for most motors in buildings and industrial facilities range from 50% to 70% [44].

Correct sizing of electric motors is critical to their efficient operation, since oversized motors tend to exhibit poor power factors and lower efficiencies. Depending on size and speed, a typical standard motor may have a full load efficiency between 55% and 95%. Generally, the lower the speed, the lower the efficiency, and the lower the power factor. Typically motors exhibit efficiencies which are reasonably constant down to approximately 75% full load. Thereafter they may lose approximately 5% down to 50% of full load, after which the efficiency rapidly falls as shown in figure [48].

It can be seen from the performance curve in the figure that it is possible to oversize a motor by up to 25% without seriously affecting its efficiency, provided that a motor is run at a relatively constant load. If the load fluctuates and rarely achieves 75% full load, then both the efficiency and the power factor of the motor will be adversely affected. In fact the power factor tends to fall off more rapidly than the efficiency under part-load conditions. Therefore, if motors are oversized, the need for power factor correction becomes greater. Oversizing of motors also increases the capital cost of the switchgear and wiring which serves the motor [48].

When a motor has a significantly higher rating than the load it is driving, the motor operates at partial load. When this occurs, the efficiency of the motor is reduced. Motors are often selected that are grossly underloaded and oversized for a particular job. For instance, field measurements made at four industrial plants in Northern California indicate that, on the average, motors are operating at 60% of their rated load. As a general rule, motors that are undersized and overloaded have a reduced life expectancy with a greater probability of unanticipated downtime, resulting in loss of production. On the other hand, motors that are oversized and thus lightly loaded suffer both efficiency and power factor reduction penalties [43]. The efficiency of motors usually peaks at close to 75% of full load. Oversized motors generally operate at a lower efficiency. For example, a motor that is operating at 35% load is less efficient than a smaller motor that is matched to the same load. Therefore, sizing a motor correctly is very important to not only prevent overheating but also to achieve maximum energy savings [77]. Fig. 6 shows that power factor tends to drop off sooner.

Based on the above discussions it has been found that motors are not used at full load and in most cases they are oversized that encourage wastes of energy. One of the best solution to overcome this problem is to use computer tools such as MotorMaster+, EuroDEEM, and CanMOST. These tools are discussed in following section.

5. Computer tools to analyze motor energy use

5.1. MotorMaster+

MotorMaster+ is a software package that was developed by the Washington State Energy office and funded by the U.S. Department of Energy and the Bonneville Power Administration to aid in the selection of energy-efficient motors. MotorMaster's database contains information on over 10,000 available motors which allows the user to compare efficiency, first cost, and operating cost of a standard-efficiency motor to an energy-efficient motor. The database contains motor technical data from 18 motor efficiency, power factor, torque, amperage, operating voltage, service factor, frame size and enclosure type. Purchase information such as manufacturers name, model name, list price, and warranty are also included. The user specifies the type of motor needed and MotorMaster+ generates a list of available models ranked in the order of efficiency. Performance and price data are given that meet given specifications. MotorMaster+ calculates the energy cost of operating the motor specified. This operating cost take into consideration annual operating hours, load factor, efficiency, and energy prices. Both energy charges and demand charges can be used in the savings calculation. MotorMaster+ calculates the simple payback of an investment allowing the user to determine the most cost-effective motor for a given application [78].

5.2. International motor selection and savings analysis (IMSAA)

IMSAA is a multiple analysis features including: motor analyzer, new motor, purchase, repair versus replace, replace existing motor (oversized/underloaded), motor selector, best available motor identification, life cycle costing. Building on experience with existing software, such as MotorMaster+ (U.S.) and EuroDEEM (Europe), an international collaboration was formed to develop software that would provide a universal, flexible software adaptable for use in any country in any language. Through the support of the sponsoring organizations: Corporacion Nacional del Cobre de Chile (Codelco); the UK Action Energy (Carbon Trust), the European Community – JRC; Natural Resources Canada; the US Department of Energy; and the International Copper Association, IMSSA seeks to provide industrial users of motor systems with greater access to performance and decision-making information concerning energy-efficient motors. In addition, the focus on international collaboration provides a unique environment for further dialogue on about the global harmonization of motor testing and energy-efficiency standards [79].

5.3. ProMot-Europe

Operates on web environment and as standalone choice of motor from 5 databases. In Europe – database of 2003 50 Hz for more than 25 manufacturers and 18,000 motor models. The motor can be chosen for:

- New installation
- Refurbishment
- Replacement of existing
- Energy and economic analysis

5.4. Canadian motor selection tool (CanMOST) [80]

Choosing an energy-efficient industrial motor can dramatically reduce the energy consumption and utility cost of running a motor-driven system over its lifetime. Analyzing the costs and benefits of different motors can be complicated, but CanMOST – the Canadian Motor Selection Tool – now makes the job simpler. Launched in June 2004, CanMOST is a software program that analyses and compares the efficiency of three-phase electric motors. With its database of over 43 000 motors, CanMOST calculates energy and electrical demand savings so one can make the most energy-efficient and cost-effective choice when it comes to buying motors for one's industrial application. CanMOST allows one to calculate energy and demand savings, predict energy and cost savings when replacing a failed or standard-efficiency motor, identify inefficient or oversized motors in your facility, select the best available premium-efficiency motor for a given application, compare operating costs of various motors, calculate the rate of return on a motor investment, calculate annual greenhouse gas emissions reductions.

Modelled on the successful U.S. industrial motor energy management software program MotorMaster+, CanMOST was developed for Natural Resources Canada by the Washington State University Extension Energy Program as part of the International Motor Selection and Savings Analysis (IMSSA) project. Other sponsors of this international effort include the International Copper Association, the United States, the United Kingdom, the European Commission and Chile. CanMOST is easy to learn and use. CanMOST's database comprises: data on 25,000 North American motors, the European Database of Efficient Electric Motor Systems (EuroDEEM), with 18,000 European motors data on some 575-V motors that are available only in Canada.

5.5. EuroDEEM international [81]

A voluntary initiative of the European Commission to Aid Industry in reducing electricity consumption in motor-driven systems. Available at no charge, EuroDEEM International is designed to support motor systems improvement planning at industrial facilities by identifying the most cost-effective choice when deciding to repair or replace older motor models. With EuroDEEM International one can evaluate repair/replacement options for a broader range of motors, including those tested under the Institute of Electrical and Electronic Engineers (IEEE) standard, and those tested using the International Electrotechnical Commission (IEC) methodology. EuroDEEM International has Multilanguage capability (with the current release supporting Spanish, French and English) and allows the user to conduct economic analyses using various currencies. The software also allows users to insert applicable country or regional motor full load minimum efficiency standards, and country-specific motor repair and installation cost defaults. EuroDEEM International can display motor performance and technical data that can help to optimize a drive system. Data is available for both 60 Hz National Electrical Manufacturers Association (NEMA) and 50 Hz metric or IEC motors. The current version of the software contains manufacturer's databases for over 25,000 NEMA motors and over 7200 IEC motors.

6. Motor energy savings

It may be mentioned that energy can be saved in different ways for different the industrial energy using machineries with different energy savings strategies. These strategies are broadly classified in three ways:

- Using regulations (voluntary, mandatory, mixed, standards, labels, education, soft loan, incentives)
- With the application of technology (VSD, power factor improvement, new technology)
- By housekeeping (maintenance, switching of, reduce standby losses, auditing)

These are elaborated below.

6.1. Mandatory/regulatory and voluntary approaches

Enforcing energy efficiency through regulatory control has the advantage that all parties concerned will be aware of the requirements, and ensures that a certain minimum level of performance is achieved across the board as can be seen in Fig. 7 for example.

However, such an interventionist approach only leads to moderate results, as the compliance criteria needs to be set at levels that are relatively easy to achieve so as not to incur heavy financial burdens on society. Rather than using regulatory instruments, many have opined that the voluntary-based environmental approaches can be more effective, because they offer greater flexibility for in reaching targets, thereby improving their image, and is more useful to policy makers in promoting a dialogue with the private sector and to raise public awareness. However, implementation experience indicates that only moderate results have been achieved through voluntary approaches. Recent findings tend to favor the adoption of a well articulated mix of regulatory and voluntary instruments. Besides setting a minimum standard, regulatory controls can also augment co-existing voluntary schemes. The voluntary schemes can benefit from the increased awareness and drive towards improvements triggered by the regulations, use the regulatory requirement as a baseline for defining enhanced performance, and provide an incentive to

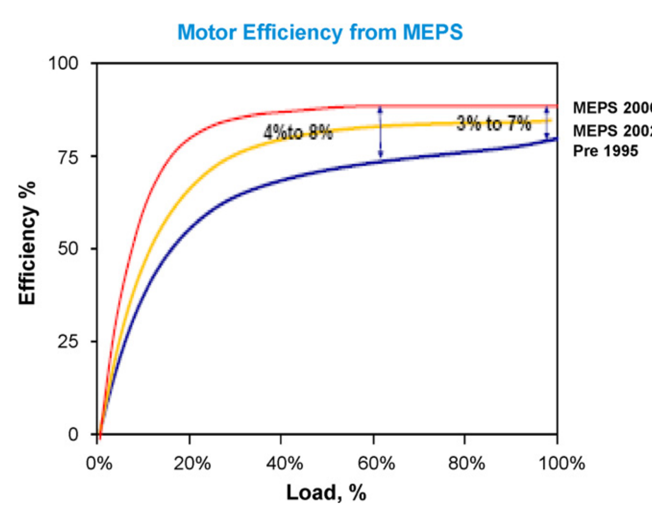

Fig. 7. Efficiency levels of MEPS.*Source*: [82].

achieve a standard above the minimum [83]. These approaches are shown below:

Mandatory/regulatory measures can be classified as:

- Minimum Energy Performance Standards MEPS
- Enforcement: Compliance measurement, sanctions
- Standard product declaration and certification
- Independent testing

Voluntary measures can be classified as:

- Labels
- Reach standards (future)
- Voluntary agreements with industry
- Public procurement programs
- Training and tools

Incentives can be classified as:

- Loans (pay as you go)
- Tax rebate for investment
- Bonus/Malus
- CDM
- Government or utility subsidy
- Free audits

However, it has to be noted that an energy test procedure which is the foundation or base of any regulatory approach must be developed first. Energy test procedures are elaborated below:

6.2. Energy test procedure

An energy test procedure is an agreed-upon method of measuring the energy performance of an appliance, machine and equipment. The results of an energy test procedure may be expressed as efficiency, efficacy (lighting), annual energy use, or energy consumption for a specified cycle, depending on the machine being tested. It should be perceived test standards as a means for providing solutions for energy efficiency.

An energy test procedure (sometimes referred to as "test standard") is the base of, and represents the technical foundation for, all energy-efficiency standards, labels and other related programs as can be seen in Fig. 8. Energy labels could not be created without an energy test procedure. While modern energy-efficiency measures like, labeling provides vital information about individual products, product testing by independent consumer bodies remains the impartial way to compare the energy performance of appliances [84].

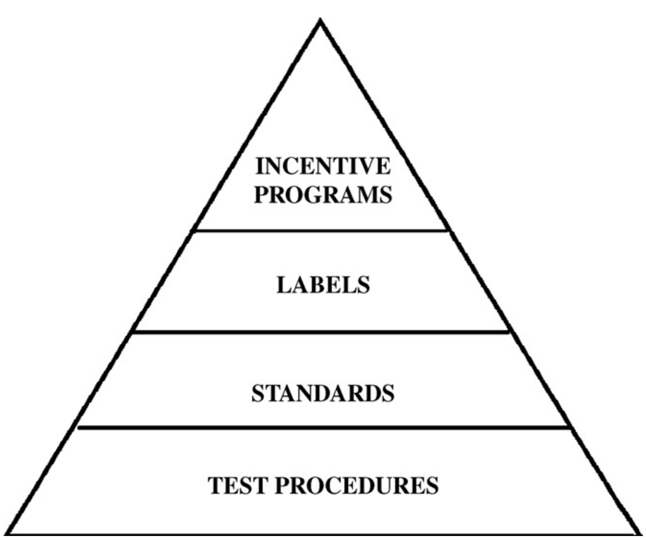

Fig. 8. Relationship among test procedure, standard and label.

The function of test standards is to establish a uniform and repeatable procedure or standard method for measuring specific machines characteristics. According to references [85,86] a good test procedure should fulfill following criteria:

- accurately reflect the relative performance of different design options for a given machine;
- reflect actual usage condition, and yield repeatable, accurate results;
- cover a wide range of models within that category of machine;
- be inexpensive to perform;
- be easy to modify to accommodate new technologies or features; and
- produce results that can be easily compared with results from other test procedures.

6.2.1. Motor efficiency testing standards

It is critical that motor efficiency comparisons be made using a uniform product testing methodology. There is no single standard-efficiency testing method that is used throughout the industry. The test methods predominantly used in the world today are IEC 60034-2-1, IEEE 112B and CSA390. The most common standards are [1,43] summarized in Table 5.

Claspononline [87] also summarized motor test standards for few selected countries around the world. This can be seen in the Table 6.

6.3. Mandatory/regulatory measures

Mandatory Energy Performance Standards (MEPS) establish standards for energy performance that products must meet or exceed before they can be sold to consumers. They improve the average efficiency of products available on the market by raising the performance of the least-efficient products. MEPS prescribe minimum efficiencies (or maximum energy consumption) that products must achieve and are enforced by law. Experience from other countries where minimum standards have been implemented shows that this is the most effective method of uplifting overall motor efficiency performance levels. Status of MEPS for few selected countries around the world are elaborated below [1].

6.3.1. USA Energy Policy Act – EPAct (1992)

It was enforced in October 1997 and requires that motors manufactured or imported for sale in the USA meet minimum efficiency levels. It is a mandatory agreement. EPAct motors now constitute 54% of the integral horsepower induction motor market share. Other motors include premium-efficiency motors and non-general purpose motors.

6.3.2. NEMA – Premium (2002)

Because many utilities and industry associations were promoting motors with a higher efficiency than EPAct mandatory levels, the National Electrical Manufacturers Association (NEMA) felt a need to define a classification scheme for premium higher efficiency motors. In 2005 NEMA Premium motors constituted 16% of the market share in USA. In the end of 2007, the US congress decided to adopt the proposal which means US will take current NEMA Premium level to become MEPS for electric motor energy efficiency by 2011.

6.3.3. Canada, Mexico and Brazil

In 1991, the Canadian Standards Association (CSA) and Canadian Electric Machinery Association drew up a recommended

Table 5
Summary of motor test standards for major economic countries.

Test standard	Purpose/scope	Country used	Remarks	Reference
IEEE 112 (2004)	To determine efficiency. To investigate performance of induction motors and generators.	USA	–	[1,43]
IEEE 113 (1985)	To determine the performance characteristics of conventional direct-current machines.	USA	Withdrawn some years ago	
IEEE 114 (2001)	To investigate the performance of single-phase induction motors.	USA	–	
IEEE 115 (1955)	To investigate the performance of synchronous machines.	USA	–	
ANSI/NEMA MG1	To select and apply proper motors and generators.	USA	–	
C390-98 (2005)	To measure the energy efficiency of three-phase induction motors rated 0.746 kW at 1800 rpm (or equivalent) and greater.	Canada	Very similar to IEEE 112-B	
CAN/CSA C22.2 No. 100-04	To investigate performance of motors and generators.	Canada	This is the Canadian equivalent to ANSI/NEMA MG1	
IEC 60034-2 (1996)	To establish methods of determining efficiencies from tests, and also specifies methods of obtaining specific losses.	EU	It applies to DC machines and to AC synchronous and inductions machines of all sizes	
IEC 61972 (2002)	This test standard, developed as a possible replacement of IEC 60034-2 in what concerns three-phase induction motors, allows two methods to determine their efficiency and losses. Method 1 – Input–output method (similar to IEEE 112-B). Stray load losses determined from measurements. Method 2 – Indirect method (assigned variable allowance)	EU	–	
IEC 60034-2-1	This new version of IEC 60034-2 was approved by 23 countries in favor, 5 abstentions and no disapprovals. It introduces the Eh-Star test as a recognized method to determine additional load losses of induction machines	EU	Because of its relative lower costs to test the large number of motor models already in the market, motor manufacturers see this method as a cost-effective alternative to upgrade the efficiency tests of those motors	
AS 1359.102	This standard establishes methods of determining efficiencies from tests, and also specifies methods of obtaining particular losses when these are required for other purposes. It applies to DC machines and to AC synchronous and induction machines of all sizes within the scope of IEC 60034-1.	Australia	It is expected that the Australian Standard will shortly collapse to follow the revised international standard IEC 60034-2	

minimum power efficiency standard for electric motors. British Columbia and Ottawa subsequently passed legislation requiring new electric motors purchased within their jurisdictions to comply with this standard, whose efficiency index is slightly lower than that later mandated under EPAct by the United States. In light of the importance of the energy problem, Canada's Parliament also passed the Energy-Efficiency Act (EEAct) in 1992. EEAct, which included minimum energy-efficiency standards for electric motors, was to take effect in 1997. Its efficiency index for electric motors was the same as that of EPAct. EEAct differs slightly from EPAct in that it applies both to electrical machinery with a voltage class of 600 V or less and to 50/60 HZ dual-frequency electric motors in addition to those of 60 HZ frequency. As this standard was legally compulsory, high-efficiency electric motors quickly saw widespread use. In 1988, high-efficiency electric motors accounted for less than 4% of Ottawa's electric motor market; by 1993, this had risen to more than 60%.

Mexico and Brazil have also worked out their own minimum energy-efficiency standards for electric motors. The efficiency index of Mexico's 1997 standard was the same as under NEMA12-9, the earlier U.S. standard for high-efficiency electric motors. The standard was later amended after Mexico signed a free-trade agreement with the U.S. in 2002. Mexico's current standard is NOM-016-ENER-2002, whose efficiency index is the same as that of EPAct. The Mexican standard has somewhat broader applications than EPAct, covering power between 0.746 kW and 373 kW (i.e. 1–500 HP) and vertical as well as horizontal installation. This standard took effect in March 2003. The minimum energy-efficiency standard for electric motors in Brazil remains the same as NEMA12-9, which is slightly lower than U.S. EPAct index.

6.3.4. EU

The EU-CEMEP agreement provides for the rating and identification of motor efficiency. Two efficiency indices—high and low—are stipulated for motors of different specifications. Motors with an efficiency value lower than the low index are classified as EFF3; those with an efficiency value between the low and the high index are EFF2; those above the high index are classified as EFF1. The loss of EFF1 motors is 40% lower than that of EFF2 motors, and they are designed for more than 6000 h of annual runtime. The loss of EFF2 motors is 20% lower than that of EFF2 motors, and they are designed for more than 2000 h of annual runtime. The efficiency of EFF1 motors, compared with EFF2 motors, has improved 1–5% according to different powers. EFF3 motors are generally known as low efficiency motors, EFF2 motors as improved efficiency motors, and EFF1 motors as high-efficiency

Table 6
Test procedures and the legal status of energy efficiency standards and labels for electric motors for selected countries [87].

Country	Test procedure	Energy labels		Efficiency standards	
		Mandatory	Voluntary	Mandatory	Voluntary
Australia	Yes	No	No	Yes	No
Brazil	Yes	Yes	No	Yes	No
Canada	Yes	No	No	Yes	No
Chile	Yes	U	U	U	U
China	Yes	No	No	No	Yes
Chinese Taipei	Yes	No	No	Yes	No
Costa Rica	No	Yes	No	Yes	No
Columbia	Yes	No	Yes	No	Yes
EU countries	Yes	No	Yes	No	Yes
India	Yes	No	Yes	No	No
Israel	Yes	No	No	Yes	No
Malaysia	No	U	U	No	Yes
Mexico	Yes	No	Yes	Yes	No
New Zealand	Yes	No	No	Yes	No
Philippines	No	U	U	U	U
South Korea	Yes	No	Yes	No	No
Poland	No	No	Yes	No	No
Thailand	Yes	No	Yes	U	U
USA	Yes	No	No	Yes	No
Vietnam	Yes	No	No	U	U

Note: U – under consideration.

motors. The agreement also requires manufacturers to identify efficiency grade on their product nameplates and sample data sheets to facilitate selection and identification for users. However, it has to be noted that cost of high-efficiency motors are very high as can be seen in Fig. 9.

6.3.5. Australia/New Zealand

In October 2001 in Australia and 1 April 2002 in New Zealand, the first stage of the mandatory MEPS program for 3 phase induction motors, MEPS1, was introduced and became mandatory for motor suppliers, manufacturers and importers. In effect, minimum efficiency levels for MEPS1 equated to European EFF2 motor efficiency levels.

The second stage, MEPS2 (also mandatory), was introduced in April 2006 in Australia and June 2006 in New Zealand. MEPS2 motor efficiency levels are similar to European EFF1 efficiency and also redefined the "High-Efficiency" levels at a higher level with nominally 15% less loss than the EFF1 levels. Three-phase motors that fall within the scope of standard AS/NZS 1359.5:2004 must be registered to be offered for sale in Australia, for New Zealand the

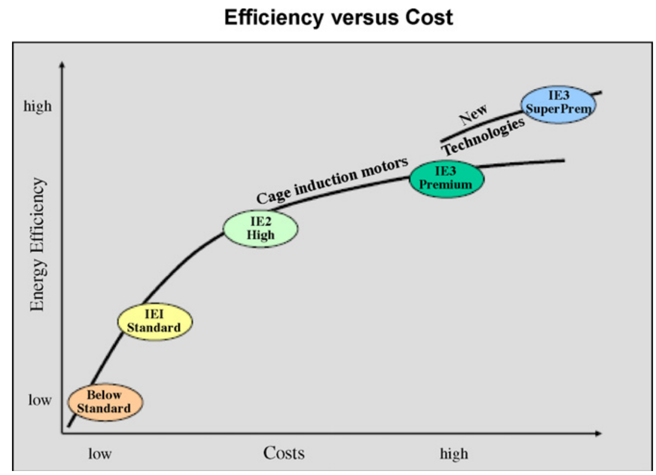

Fig. 9. Cost of high-efficiency motors.

prescribed forms need to be completed and submitted to EECA before being available for sale. The range and scope of motors affected by this new standard are single speed three-phase cage induction motors from 0.73 kW up to but not including 185 kW, for voltages to 1100 V.

6.3.6. Australian Energy Performance Program – MEPS (AS 1359.5:2004)

The new Australian Energy Performance Program – MEPS (AS 1359.5:2004) – has efficiency levels equivalent to EFF1/EPact. This is a mandatory measure starting in April 2006.

Two methods of efficiency measurement, described in AS 1359.102, are allowed: Method A, identical to method 1 of IEC 61972 and technically equivalent to method B specified in IEEE 112; Method B based on IEC 60034-2 "summation of losses" test procedure. Equipment Energy Efficiency (E3) periodically reviews current MEPS levels for each product in light of international developments. Table 7 shows the voluntary and mandatory regulations around the world.

6.4. Voluntary approaches

Voluntary instruments for minimizing environmental impacts include codes and eco-labeling schemes through which organizations commit to make their products or production processes more

Table 7
Motor efficiency voluntary agreements and regulation around the world [1].

Country/region	Mandatory agreements (year of implementation)	Voluntary agreements (year of implementation)	Market share
U.S.A.	EPAct-high efficiency (1997) NEMA Premium (2011)	NEMA Premium (2001)	NEMA Premium (16%) EPAct (54%)
Canada	EPAct levels-high efficiency (1997)	NEMA Premium (2001)	NEMA Premium (16%) EPAct (54%)
Mexico	EPAct levels-high efficiency (1998)	NEMA Premium (2003)	N/A
EU	–	Efficiency classification and market reduction of EFF3 (1998)	EFF1 (12%) EFF2 (85%) for CEMEP members
Australia	High efficiency (2006)	Premium efficiency (2006)	Premium efficiency (10%) High efficiency (32%) Standard efficiency (58%)
New Zealand	High efficiency (2006)	Premium efficiency (2006)	N/A
Brazil	Standard efficiency (2002) High efficiency (2009)	High efficiency	High efficiency (15%)
China	Standard efficiency (2002) High efficiency (2011)	Premium efficiency (2007)	High efficiency (10%) Standard efficiency (90%)
Korea	Standard efficiency (2008)	Standard efficiency (1996)	High efficiency (10%) Standard efficiency (90%)

environmentally friendly. Market forces encourage participation if compliance with a voluntary scheme or attainment of an eco-label is perceived to be of value to the end users of products (tenants or property buyers in the case of buildings). The offer of rebates to encourage participation is also widely adopted in voluntary instrument, since rebates effectively lower the cost of implementing improvement measures.

Since the early 1990s there has been a significant increase in the use of voluntary approaches to deal with various environmental problems, including GHG emissions. The number of voluntary instruments in use is more than 30,000 in Japan, in excess of 30 in the EU, and the US has 42 initiatives in existence. The extremely large number of cases in Japan compared to other countries lies in that voluntary instruments are used in almost every sector, from controlling pollutant emissions from power plants to small manufacturing factories; and from the manufacturing sector to services sector. According to Hashimoto this follows from the Yokohama Environmental Agreement signed in 1964 between the local governments and the industries concerned, and is an excellent example of resolving environmental issues by voluntary instruments. Voluntary instruments may be classified with reference to the parties involved, namely unilateral commitments made by polluters, negotiated agreements made between industry and public authorities, and voluntary programs developed by public authorities [83].

In Sweden, policy instruments such as taxing industries for CO_2 emissions, information campaigns, and regulatory legislation have been used. These strategies are considered to be successful as far as they concern activities that can be controlled and measured quantitatively. Regarding promotion of motivation for behavioural change, planning for investments in more-efficient technology or changing attitudes and values towards energy use, combinations of policy instruments will be more fruitful. From a theoretical perspective, voluntary agreements include commitments made by individual companies or by trade and industry and are a result of negotiations with public authorities and/or have been accepted by them. The definition spans a broad spectrum ranging from voluntary commitments and non-binding agreements to legally binding agreements. Voluntary agreements are the results of cooperation and negotiation between two partners, an authority and an industry, and are intended to be followed by some form of contract. From the voluntary basis of cooperation there also follows a variation in content between agreements aimed to fulfil the same purpose. Sweden has less experience with voluntary agreements than, for example, The Netherlands and Germany. A survey conducted in 2000 revealed that there were 17 examples of environmental agreements reached in Sweden in the 1990s. This can be compared to the over 100 voluntary agreements that have been concluded in the Netherlands (Nilsson, 1998). There is also a variation between countries in the ways voluntary agreements are used, e.g. as an instrument per se or in combination with other instruments. In Denmark, for example, the laws have been revised to make it possible to expand voluntary agreements in a binding way.

The strength of voluntary agreements as a policy measure seems to be more effective when combined with other policy instruments. In the Swedish EEP case, the education programme (ENEU) and, the energy and environmental audits were appreciated and considered very important for the Swedish companies. Information and advising functions seem to be very important throughout the entire process of a programme, and must not be underestimated in terms of time and costs. Such aspects were very much asked for, and evaluated as insufficient, especially in the final phases of the programme [88].

The Department of Industry, Tourism and Resources has in place several assistance programs to voluntarily encourage the use and promotion of high-efficiency three-phase electric motors. NAEEEC wants to explore whether suppliers are interested in other voluntary programs that can identify "high-efficiency" products and reduce greenhouse gas emissions [89].

Technology analysts assert that carefully designed regulatory interventions can stimulate actions that yield simultaneous reductions in energy use and the effective cost of energy services. The US National Academy of Sciences, for example, identified the potential to improve energy efficiency by up to 37% at zero economic cost. Similarly, the Intergovernmental Panel on Climate Change concluded that global carbon dioxide emissions could be cut by 30% through the accelerated diffusion of least-cost energy technologies [90].

The Green Lights program and The Energy Star Office Products program are two successful voluntary program designed get success in US. These case studies suggest that voluntary agreements between government agencies and private-sector firms can if well designed lead to improvements in both the technical efficiency of energy use and the economic efficiency of resource allocation [90].

Krarup [91] gave an overview of the state-of-the-art of the recent literature on the efficiency of voluntary approaches, and to point at preconditions for efficient voluntary approaches in the literature.

EU Member States have shown a clear preference for voluntarily negotiated agreements with sectors. In total, more than 20 voluntary agreement programmes are operational in EU countries, addressing energy efficiency/climate change issues and these form an important pillar of the EU policy. According to the European Commission's Communication "Action Plan to Improve Energy Efficiency in the European Community" mentioned, long-term agreements are a key instrument to promote energy efficiency [92]. US is also looking to develop voluntary Super Premium levels (the proposed IE4 level in the draft IEC standard).

6.4.1. Energy guide label

Labelling provides information on a product's energy performance at the point of sale, allowing consumers to make more informed purchasing decisions. The following information is displayed on an energy rating label:

- Energy performance information
- A star rating to allow consumers to compare the energy performance of competing models at a glance
- An estimate of the model's annual energy use.

The energy guide label provides information on energy consumption for comparative purposes. It is a mandatory or voluntary sticker that is affixed to products or their packaging and that contains information on the energy efficiency or energy consumption of the product. Labeling is the most effective way of selecting the most preferable equipment available in the market for one's need. The label shows how the energy use of the labeled model compares with the energy use of the most- and least-efficient models of comparable size and features available on the market. Most energy guide labels show the yearly energy cost of operating a machine/appliance [93]. When considered along with the purchase price, the label will help to determine which machine is less expensive to own and operate over its life span [94]. Energy labels also serve as a complement to energy-efficiency standards. The labels provide information to the consumers so they can select the more-efficient models. Labels also allow utility companies and government energy conservation agencies to offer incentives to the consumers to buy the most energy-efficient products. The effectiveness of energy labels is highly dependent on how information is presented to the consumer [87]. An important aspect of the label is the ability to

Table 8
Energy savings and payback period for high-efficient motor.

HP	Quantity (no)	Incremental price (US$)	Load (50%)			Load (75%)			Load (100%)		
			Energy savings (MWh)	Bill savings (US$/year)	Payback (year)	Energy savings (MWh)	Bill savings (US$/year)	Payback (year)	Energy savings (MWh)	Bill savings (US$/year)	Payback (year)
1	3968	24	74	4730	2.05	96	6118	1.59	127	8158	1.19
1.5	331	21	6	394	1.80	7	458	1.55	10	611	1.16
2	1653	25	28	1814	2.25	53	3421	1.19	71	4562	0.89
3	2976	27	122	7798	1.02	174	11,155	0.71	232	14,873	0.53
4	13,556	60	393	25,169	3.22	620	39,675	2.04	827	52,900	1.53
5.5	331	65	16	1022	2.10	12	792	2.71	16	1056	2.04
7.5	661	91	19	1194	5.05	25	1598	3.77	33	2131	2.83
15	165	147	21	1351	1.80	31	1957	1.24	41	2609	0.93
20	3306	197	404	25,888	2.52	811	51,883	1.26	1081	69,177	0.94
25	992	246	156	9989	2.44	282	18,046	1.35	376	24,061	1.01
30	331	257	11	682	2.33	82	5261	1.62	110	7014	1.21
40	661	231	140	8938	1.71	123	7852	1.95	164	10,469	1.46
50	331	281	58	3721	2.50	152	9746	0.95	203	12,994	0.71
60	827	574	257	16,417	2.89	130	8295	5.72	173	11,060	4.29
75	165	518	60	3862	2.22	106	6763	1.27	141	9018	0.95

provide consumers a method of comparing similar units of a product. This has been done in some cases by showing the energy consumption or efficiency of a particular model on a scale that also shows the lowest and highest energy consuming model [95]. By educating consumers, labeling serves to create competition among the manufacturers. Thus, labeling not only forces manufacturers to comply with baseline efficiency but also encourages them to seek increased market share by improving their products at a reduced cost [96]. Table 6 shows the summary of motor energy guide labels around the world.

7. Quantification of energy savings

Switching to energy-efficient motor-driven systems can save Europe up to 202 billion kWh in electricity use, equivalent to a reduction of €10 billion per year in operating costs for industries. It was reported that a reduction of 79 million ton of CO_2 emissions (EU-15), or approximately a quarter of the EU's Kyoto target is achievable using energy-efficient motors. This is the annual amount of CO_2 that a forest the size of Finland transforms into oxygen. If industries are allowed to trade these emission reductions based on energy saved, this would generate a revenue stream of €2 billion per year. For EU-25, the reduction potential is 100 million ton [35]. Ruddell [97] believes that legislation relating to products will eventually lead to more-efficient systems, commenting: "Even the voluntary scheme for motors introduced in Europe several years ago has encouraged manufacturers to move from very low efficiency levels where around 40–50% of all motors sold in Europe were of efficiency level three below. Today, something like 90% of all motors meet efficiency level two and 10% efficiency level one. This has moved the efficiency threshold upwards and that has to be a good thing. Saidur et al. [11,12] estimated energy savings, bill savings and emission reduction associated with energy savings and their findings are presented in Table 8. Garcia et al. [98] reported efficiency and cost of standard and energy-efficient motors for different capacities, loadings and poles. Cost of different sizes of motors can be found in Capehart et al. [47] as well.

Installing high-efficiency motors in compressor systems reduces annual energy consumption by 2%, and has a payback period of less than 3 years [99]. Christina and Worrell [100] reported that delta Extruded Metals (UK) replaced five motors used to operate its furnaces with new high-efficiency motors. For the sum of motors, they realized a savings of 11,660 kWh/year, equivalent to US$ 765, and implementation costs of US$ 1250, yielding an average payback period of 1.6 years. The total savings of electricity and greenhouse gas are estimated at 3324 GWh and 2 $MTCO_2$, respectively [101]

Elliot [103] estimated energy savings associated with high-efficient motors and summary of savings presented in Table 9.

8. Payback period

Cost premiums for high-efficiency motors range from 10% to 30%, but since a motor may use 75% its initial cost in electric energy over its life time, the savings potential is great. Return on investment can be obtained within short period of time (i.e. 2–3 years) [47].

The costs of high-efficiency motors that have been developed in the last years are more expensive, around 15–25% more than that of standard motors [102]. Usually, because of the low operating costs, this difference can be regained in a short time. By increasing the cross section of the copper conductors that are used in the motor winding, the primary I^2R loss can be decreased. Iron core loss with the decrease of flux density, usually, can be limited by increasing the neck of the stator core. Beside, these losses can be decreased by decreasing the thickness of the panels and using good quality alloys. On the other hand, in high-efficiency motors, because of the decreased losses, the need of disposing of the revealed heat decreases [13].

9. Energy savings by using technology

Energy savings by technology includes use of VSDs to match the load requirements and capacitors to reduce losses thus improving motor power factor. These are elaborated below.

Table 9
Energy using high-efficient motors [103].

Motor HP	Energy savings (kWh/year)
1	111
5	301
20	10,20
50	1604
100	7141
200	5213
500	25,880

9.1. Motor energy savings using variable speed drive (VSD)

9.1.1. Constant speed drive

In about 25% of the applications that induction motors are used, there is no need to operate the motor at full load. For example, in the water supply industry, constant speed drives will operate the pump at 100% of the motor rated speed, then the valves are placed in the pipeline and are adjusted to restrict the flow of water. In other industries, reduction gears are placed after the electric motor to reduce the speed or torque. The cost of valves, gears, and excess electric energy can be an additional unnecessary cost once output power is clamped down. Constant speed motor starters cannot adjust their speed, so that anytime there is need for the speed of a motor to operate [104].

9.1.2. ASD

9.1.2.1. Definition and application. Variable-frequency drives provide continuous control, matching motor speed to the specific demands of the work being performed. Variable-frequency drives are an excellent choice for adjustable speed drive users because they allow operators to fine-tune processes while reducing costs for energy and equipment maintenance [1,44,104]. VSDs can be classified as shown in Fig. 10.

Electric motors are over 90% efficient when running at their rated loads. However, they are very inefficient at load-following, or running at part loads. Conventional electric motors typically use 60–80% of their rated input energy, even when running at less than 50% load. It is very important to select an electric motor of suitable power to work efficiently. In general, motors are chosen in big capacities to meet extra load demands. Big capacities cause motors to work inefficiently at low load. Normally, motors are operated more efficiently at 75% of rated load and above. Motors operated lower than 50% of rated load, because they were chosen in big capacity, performing inefficiently, and due to the reactive current increase, power factors are also decreased. These kinds of motors do not use the energy efficiently because they have been chosen in for large motor power, not according to the needs. These motors should be replaced with new suitable capacities of motors, and when purchasing new motors, energy saving motors should be preferred [13].

9.1.2.2. Applications of VSDs. Adjustable speed motors conserve energy by operating motors at levels only necessary for the particular task at a given time. Motors without adjustable speed may often operate at a single level that is well above the necessary speed for a particular application and, therefore, be quite wasteful of energy. The problem is exacerbated by the fact that most facilities choose to install oversized motors that operate at levels well above the necessary speed in order to have spare capacity should the required load unexpectedly increase for a new application at some point in the future. On average, these motors operate at no more than 60% of their rated load because of oversized installations or under-loaded conditions, and thus at reduced efficiency which results in wasted energy [4]. Adjustable speed motors can be used for a variety of applications including fans, pumps, compressors, conveyors, and robots. They are particularly well suited to instances where the applications do not require full output all the time and when manufacturers insist on having extra capacity. The adjustable speed motor allows for flexibility without requiring a continuous high use of energy to operate.

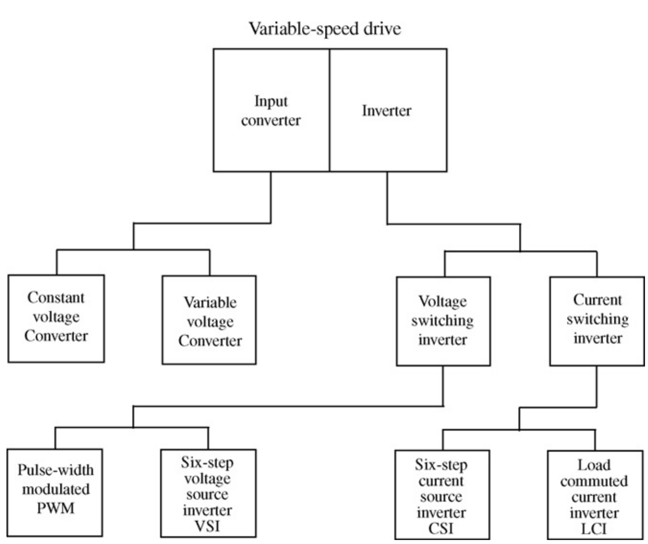

Fig. 10. Classification of VSD [105].

Table 10
Potential savings from VSD [106].

Average speed reduction (%)	Potential energy savings (%)
10	22
20	44
20	61
40	73
50	83
60	89

Adjustable speed motors can provide significant savings in energy usage and costs. Energy used by electric motors generally represents up to about 75% of an industrial plant's entire energy use and about two-thirds of the motors in industrial use are for fans and pumps which do not need constant motor speeds. So any increase in the energy efficiency of such machines will result in significant savings. The department of energy estimates that replacing conventional motors with adjustable speed motors in appropriate applications would result in saving 41% of the energy used in industrial motors. Power consumption actually drops far more than the drop in motor speed, so the savings can accumulate quickly. For example a 10% reduction in shaft speed results in a 27% decrease in power consumption [3]. Table 10 shows the energy savings associated with the speed reductions as a result of using VSDs.

Many building systems are designed to operate at maximum load conditions. However, most building systems operate at their full load only for short periods of time. This often results in many systems operating inefficiently during long periods of time. Most such inefficient operations in buildings are encountered in air conditioning systems that are normally sized to meet peak load conditions, which are experienced only for short periods of the day. The efficiency of such systems can be improved by varying their capacity to match actual load requirements. As all these are variable torque applications, the power required (to drive the pumps or fans) varies to the cube of the speed and, therefore, large power reductions result from small reductions in speed as can be seen in Table 10. The most common method is to modulate the speed of the motors of pumps and fans to vary their capacity using VSDs [48].

Qureshi and Tassou [105] reviewed the VSD in refrigeration application to reduce energy uses. Variable-frequency drives (VFDs) are routinely used to vary a pump and fan speed in heating, ventilating and air conditioning of buildings as can be seen in Fig. 11. In these applications, speed control is used to regulate the flow of water or air because speed adjustment is an energy-efficient method to control the flow. The improving performance of the VFDs has resulted from rapidly evolving semiconductor

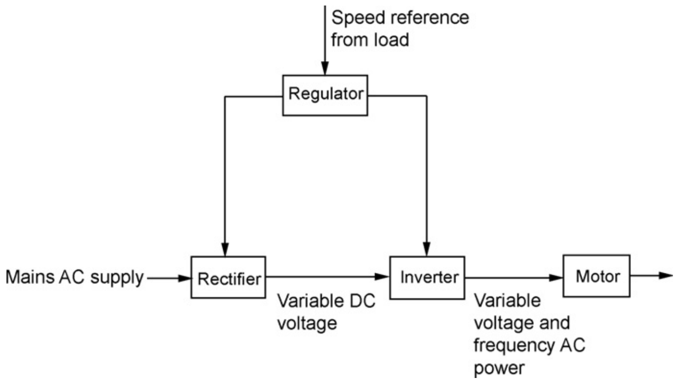

Fig. 11. Components of a variable speed drive [107].

technology. Among the improved performance characteristics are improving electrical characteristics; ability to handle higher power levels; easier programming of desired control response steadily increasing reliability and ruggedness and smaller size of units [107].

Most induction motors used in buildings are fitted to fans or pumps. The traditional approach to pipe work and ductwork systems has been to oversize pumps and fans at the design stage, and then to use commissioning valves and dampers to control the flow rate by increasing the system resistance. While mechanical constrictions are able to control the flow rate delivered by fans and pumps, the constriction itself increases the system resistance and results in increased energy loss. This situation is highly undesirable and is one of the main reasons why the energy use associated with fans and pumps is so high in many buildings. An alternative approach to the use of valves and dampers is to control the flow rate by reducing the speed of the fan or pump motor [48].

A pump installation is often sized to cope with a maximum predicted flow, which, may never happen. This principle of over sizing is frequently used in industries, which subsequently leads to energy loss and damage the parts of the pump installation.

The benefits of using VSD include:

- Energy cost savings
- Reliability improvements
- Simplified pipe systems (elimination of control valves and by-pass lines)
- Soft start and stop
- Reduced maintenance
- All amounting to lower life cycle costs.

ASD installations can increase energy efficiency (in some cases energy savings can exceed 50%), improve power factor and process precision, and afford other performance benefits such as soft starting and over speed capability. They also can eliminate the need for expensive and energy-wasting throttling mechanisms such as control valves and outlet dampers [48].

9.2. *Quantification of energy savings with the use of VSDs*

Lönnberg [108] applied variable speed drive in pumping systems in a hospital and showed huge savings potentials as pumps in a hospital have to operate 24/7. Author also estimated that $11,855 USD per year can be saved using VSDs for pumps in a hospital.

At the metal plating facility in Burlington, Vermont, General Dynamics Armament Systems installed ASDs along with an energy management control system (EMS) to control the ASDs as a unit. They found electricity savings of 443,332 kWh. The project cost $99,400 to implement, and saved $68,600 annually, providing a simple payback period of 1.5 years. The installation also reduced CO_2 emissions by 213,000 kg/year, improved overall productivity, control, and product quality, and reduced wear of equipment, thereby reducing future maintenance costs [100].

Another example of the use of ASDs was in the pumping of machine coolant at an U.S. engine plant. Pressure at the pumps was reduced from 64 psi to 45 psi, average flow cut in half, and power usage reduced by over 50% with no adverse effect on part quality or tool life [109]. Reducing the coolant system pressure also reduced the misting of the coolant, reducing the ventilation requirements and cleaning costs. ASDs can also be used in draft fans on coal-fired boilers, instead of dampers. The average electricity savings depend on boiler load, but will typically exceed 60% annually [109].

Yu and Chan [110] reported that load-based speed control for all-variable speed chiller plants to optimize their environmental performance. Authors developed thermodynamic-behaviour chiller system models to perform environmental assessment (in terms of annual electricity and water consumption) for typical constant speed and all-variable speed chiller systems operating for the cooling load profile of a local office building. Authors found that the application of load-based speed control to the variable speed

Table 11
Motor energy savings with VSD for different % of speed reduction [11,12].

Motor power (HP)	Energy savings (MWh)					
	10% speed reduction	20% speed reduction	30% speed reduction	40% speed reduction	50% speed reduction	60% speed reduction
0.25	1140	2279	3160	3781	4299	4610
0.5	570	1139	1580	1890	2149	2305
0.75	977	1954	2709	3242	3686	3953
1	3907	7815	10834	12,965	14,741	15,807
1.5	489	978	1356	1622	1845	1978
2	3255	6511	9027	10,802	12,282	13,170
3	8792	17,583	24,377	29,172	33,168	35,566
4	53,395	106,791	148,051	177,176	201,446	216,009
5.5	1793	3585	4971	5948	6763	7252
7.5	4882	9763	13,536	16,199	18,418	19,749
15	2437	4874	6758	8087	9195	9860
20	65,110	130,219	180,531	216,046	245,641	263,398
25	24,421	48,842	67,713	81,034	92,134	98,794
30	9778	19,557	27,112	32,446	36,891	39,558
40	26,036	52,072	72,191	86,392	98,227	105,327
50	16,297	32,594	45,187	54,077	61,485	65,929
60	48,862	97,724	135,480	162,132	184,342	197,668
75	12,186	24,372	33,788	40,435	45,974	49,298

chiller plant can reduce the annual total electricity use by 19.7% and annual water use by 15.9% relative to the corresponding constant speed plant. Authors also showed that power consumption can be reduced from 13,500 W to 365 W by using variable speed drive. Saidur et al. [11,12] estimated potential energy savings for different percentage of speed reduction using variable speed drive and savings are presented in Table 11. Keulenaer et al. [111] showed the energy savings for European countries for using VSDs in motors and presented the savings in Table 12.

Almeida et al. [2] estimated energy savings for motors using VSDs for selected industries and presented the savings in Table 13.

Table 14 shows the installation cost, cost savings and payback period of ASDs.

The cost of an adjustable speed motor can vary quite a bit depending upon the particular features and durability. Per horsepower costs decrease significantly with size, from an average of about $640 per horsepower for a 20 horsepower application to about $150 per horsepower for a 20,000-horsepower application [3]. It was mentioned in the reference that a 10 HP, 460 V drive with line reactor will cost about $1300. Installation time, materials and start-up will cost $500 or more [112].

First costs for variable-frequency drives are relatively expensive. Installed drives range from about $3,000 for a 5 HP motor to almost $45,000 for a custom-engineered 300 HP motor, and more for larger versions [113].

Table 12
Overview of energy savings potential for motor systems in the EU [111].

Savings potential (billion kWh/year)					
EU-15	EU-25	France	Germany	Italy	UK
45	50	8	10	7	6

Table 13
Estimated technical savings potential in TWh by the year 2015 in industry and in the services sectors [2].

Industry type	Savings (TWh) by VSDs
Basic chemistry	15.5
Food, beverage, and tobacco	8.0
Iron and steel	6.3
Machinery and metal	6.4
Non-metallic mineral	7.4
Paper and cardboard	15.4
Other industries	11.9
Total industry in EU	71.0
Total services	24.6

9.3. Motors energy savings using capacitor bank

A power factor (PF) is the ratio of the real power to the apparent power and represents how much real power an electrical equipment utilizes. It is a measure of how effectively electrical power is being used. A power factor is also equal to the cosine of the phase angle between the voltage and current waveforms. Electrical loads demand more power than they use. Induction motors convert at most 80–90% of the delivered apparent power into useful works. The remaining power is used to establish an electromagnetic field in the motor. The field is alternately expanding and collapsing (once each cycle) so the power drawn into the field in one instant is returned to the electric supply system in the next instant. Therefore, the average power drawn by the field is zero and a reactive power does not register on a kilowatt-hour meter. Although it does no useful work, it circulates between the generator and the load and places a heavier drain on the power source as well as the transmission and distribution system [114].

An induction motor requires both active and reactive power to operate. The active or true power, measured in kW, is consumed and produces work or heat. The reactive power, expressed in kVARs, is stored and discharged in the inductive or capacitive elements of the circuit, and establishes the magnetic field within the motor that causes it to rotate. The total power or apparent power is the product of the total voltage and total current in an AC circuit and is expressed in KVA. The total power is also the vector sum of the active and reactive power components. Power factor is the ratio of the active to the total power [43] as can be seen in Fig. 12.

The power factor can be defined as:

$$\mathrm{PF} = \frac{\text{active power (kW)}}{\text{apparent power (kVA)}} = \frac{P}{S} = \cos\theta \tag{1}$$

$$S = \sqrt{P^2 + Q^2} \tag{2}$$

Table 14
Installation cost, cost savings and payback period of ASDs [104].

	Mfg. ASD estimated costs	200 HP constant speed	Additional costs of ASD purchase
6-Pulse 200-HP drive	$31,000	$20,000	$11,000
12-Pulse 200-HP drive	$46,000	$20,000	$26,000
6-Pulse 200-HP drive	$51,000	$20,000	$31,000
Plus rebate per installed ASD	−$7,200	$0	($7,200)
ASDs post installation annual savings			
Use motor operating value (MOV) vs. check valve	$2,500	$5,000	($2,500)
Additional maintenance costs	$0	$2,000	($2,000)
Man-hours to adjust limit switches	$0	$3,600	($3,600)
Energy cost of maintaining flow set-point ($0.45 or $0.35 × 2000 cubic of water × 365 days)	$33,215	$42,705	($9,490)
Total annual savings			($17,590)

Actual costs for installing an ASD	6-Pulse	12-Pulse	18-Pulse
Estimated costs of varying pulse ASDs	$31,000	$46,000	$51,000
Less: Rebate	−$7,200	−$7,200	−$7,200
Less: Energy savings	−$17,590	−$17,590	−$17,590
Net costs for installing an ASDs	$6,210	$21,210	$26,210

Estimated time to recoup remaining initial costs		Number of years
6-Pulse 200-HP drive – ASD	$6,210/$17,590	=0.4
12-Pulse 200-HP drive – ASD	$21,210/$17,590	=1.2
6-Pulse 200-HP drive – ASD	$26,210/$17,590	=1.5

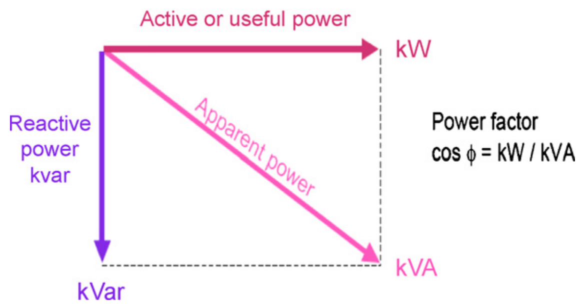

Fig. 12. Real, apparent and reactive power [115].

where

P: active power (kW),
Q: reactive power (kVAR)
S: apparent power (kVA)

In electrical systems, all inductive loads fed by alternating current draw active and reactive powers from the line. While the active power is converted into heat, light and mechanical energy or other types of energy, the reactive power cannot be converted. It causes the transformer, alternator, cable, protection relay and other equipment to be larger than their rated values. Therefore, reducing the capacities of production, transmission and distribution of the line is the result of the effects of lower power factor. In order to get rid of this effect, the power factor needs to be corrected [116].

Adding capacitors is generally the most economical way to improve a facility's power factor as can be seen in Fig. 13. While the current through an inductive load lags the voltage, current to a capacitor leads the voltage. Thus capacitors serve as a leading reactive power to counter the lagging current in a system.

The choice of the optimum type, size, number, and strategic locations for capacitors in the plant is very important. There are three methods of improving a power factor using capacitors:

a) Individual motor compensation (static capacitors)
b) Centralized compensation located at the incoming power source (automatic capacitor banks)
c) Use of synchronous motor (in overexcited mode) as synchronous capacitors

The greatest power factor correction benefits are derived when the capacitors are placed at the source of reactive currents. It is thus common to distribute capacitors on motors throughout an industrial plant. This is a good strategy when capacitors must be switched to follow a varying load [115]. Location of capacitors in motor systems is shown in Fig. 14.

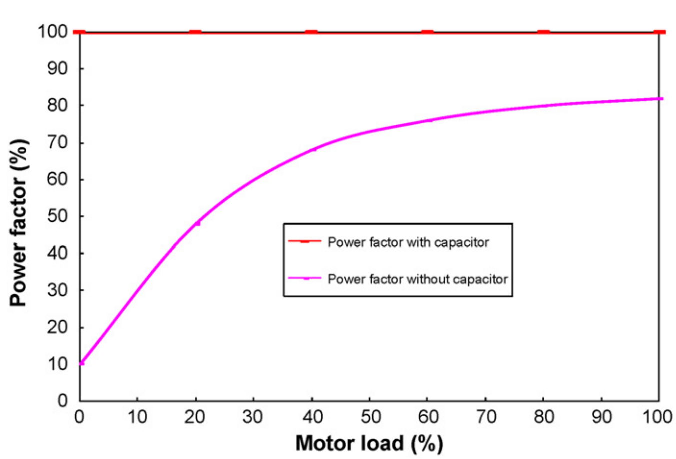

Fig. 13. Power factor improvements by using capacitor [114].

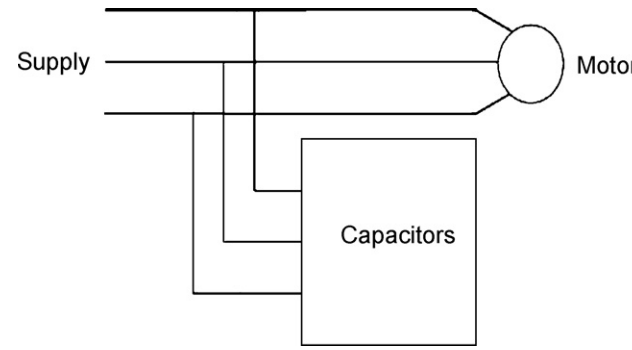

Fig. 14. Static power factor correction [44].

If the plant contains many small motors (in the 1/2 to 10 HP size range), it may be more economical to group the motors and place single capacitors or banks of capacitors at, or near, the motor control centers. In Malaysia, the capacitors are generally placed at a central location (at the incoming substation) and switched into the system automatically when the motors are started. Thus will save cost as most of the time, all the motors are not used simultaneously.

Not only improvement of the power factor will save money, additionally, it also maximizes the capacity of power system, improves the quality of voltage, and reduces the power losses. In order to decrease the cost and to improve the efficiency, the reactive power drawn from the line has to be declined by supplying it from other reactive power source. Capacitors and synchronous motors have been mostly used to compensate the reactive power in applications [38].

When a utility serves an industrial plant that has a poor power factor, the utility must supply higher current levels to serve a given load. For example in a situation where real power demand (kW) at two plants is the same, but one plant has an 85% power factor while the other has a 70% power factor, the utility must provide 21% more current to the second plant to meet that same demand. Conductors and transformers serving the second plant would need 21% more carrying capacity than those provided to the first plant. Additionally, resistance losses (I^2R) in the distribution conductors would be 46% greater in the second plant [115].

It is important not to overcorrect (as shown in Fig. 15), as overcorrection may result in greater problems such as over voltage and insulation breakdown. It is recommended that the power factor be kept above 90% and below unity (100%) for an optimal performance of the electrical system.

How much the voltage leads the current is referred to as power factor. The higher the PF, say 90% as compared to 70%, the closer the current occurs to the voltage. The lower the PF, the greater the time delays between peak voltage and peak current. The lower the PF, the greater the time delays between peak voltage and peak current [117]. Fig. 16 shows power factor for under correction.

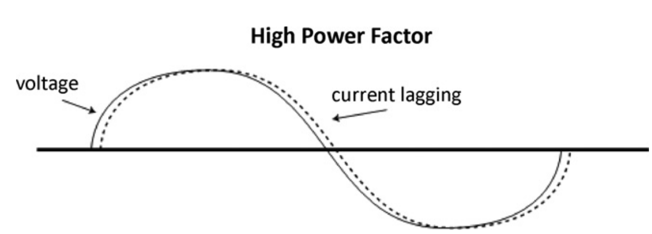

Fig. 15. Over correction of power factor (Pacific Power, 2009) [117].

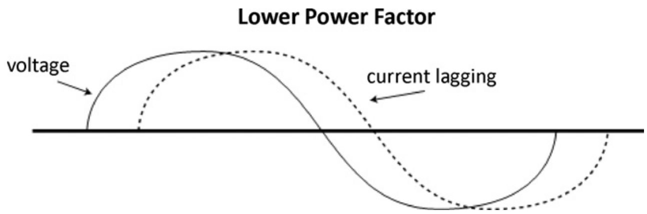

Fig. 16. Under correction of power factor [117].

9.3.1. Size and cost of capacitor

In the case of a centralized compensation, it is recommended that the first capacitor step be equal to half the value of the following steps, to allow a smooth overall linear correction system. Table 15 can be used in calculating capacitor values for a specific application. The correct capacitor size can be calculated by multiplying the factor when crossing the horizontal and vertical columns in the table by kW.

The average installed cost of capacitors per kVAR at higher voltage levels (2400 V and up) is generally about \$6–\$12 per kVAR [115].

Yang [118] reported that the 2006 constant market price of a capacitor bank: US\$ 11.4/kVAR and costs to consumer: (i) investment: \$11.4/kVAR; (ii) O&M costs: \$0.57/kVAR/year (5% of investment cost).

9.4. Energy savings in other ways

Motor service lifetimes can be extensive, typically exceeding 10 years, when the unit is properly matched to its driven load and operated under design power supply conditions. Historically, the single largest cause of motor failure has been overloading due to improper matching of motors to the load or placing motors into operation under conditions of voltage imbalance. Table 16 shows the causes of motor failure [43].

9.4.1. Switching the motor off

Motor should be switched off according to a fixed programme or schedule. System conditions, e.g. high or low temperature should be monitored, and switch off the motor when it is not needed. Sense the motor load so that the motor is switched off when ''idling''. It should be checked whether the maintenance programmes are adequate or not. Should check whether losses

Table 15
Multipliers to determine capacitor kilovars required for power factor correction [115].

Existing PF (Cos ø) before applying capacitors	Target power factor required (Cos ø)						
	0.80	0.85	0.90	0.92	0.95	0.98	1.0
0.40	1.54	1.67	1.81	1.87	1.96	2.09	2.29
0.42	1.41	1.54	1.68	1.73	1.83	1.96	2.16
0.44	1.29	1.42	1.56	1.61	1.71	1.84	2.04
0.46	1.18	1.31	1.45	1.50	1.60	1.73	1.93
0.48	1.08	1.21	1.34	1.40	1.50	1.60	1.83
0.50	0.98	1.11	1.25	1.31	1.40	1.53	1.73
0.52	0.89	1.02	1.16	1.22	1.31	1.44	1.64
0.54	0.81	0.94	1.07	1.13	1.23	1.36	1.56
0.56	0.73	0.86	1.00	1.05	1.15	1.28	1.48
0.58	0.65	0.78	0.92	0.98	1.08	1.20	1.40
0.60	0.58	0.71	0.85	0.91	1.00	1.13	1.33
0.61	0.55	0.68	0.81	0.87	0.97	1.10	1.30
0.62	0.52	0.65	0.78	0.84	0.94	1.06	1.27
0.63	0.48	0.61	0.75	0.81	0.90	1.03	1.23
0.64	0.45	0.58	0.72	0.77	0.87	1.00	1.20
0.65	0.42	0.55	0.68	0.74	0.84	0.97	1.17
0.66	0.39	0.52	0.65	0.71	0.81	0.94	1.14
0.67	0.36	0.49	0.63	0.68	0.78	0.90	1.11
0.68	0.33	0.46	0.59	0.65	0.75	0.88	1.08
0.69	0.30	0.43	0.56	0.62	0.72	0.85	1.05
0.70	0.27	0.40	0.54	0.59	0.69	0.82	1.02
0.71	0.24	0.37	0.51	0.57	0.66	0.79	0.99
0.72	0.21	0.34	0.48	0.54	0.64	0.76	0.96
0.73	0.19	0.32	0.45	0.51	0.61	0.73	0.94
0.74	0.16	0.29	0.42	0.48	0.58	0.71	0.91
0.75	0.13	0.26	0.40	0.46	0.55	0.68	0.88
0.76	0.11	0.24	0.37	0.43	0.53	0.65	0.86
0.77	0.08	0.21	0.34	0.40	0.50	0.63	0.83
0.78	0.05	0.18	0.32	0.38	0.47	0.60	0.80
0.79	0.03	0.16	0.29	0.35	0.45	0.57	0.78
0.80		0.13	0.27	0.32	0.42	0.55	0.75
0.81		0.10	0.24	0.30	0.40	0.52	0.72
0.82		0.08	0.21	0.27	0.37	0.49	0.70
0.83		0.05	0.19	0.25	0.34	0.47	0.67
0.84		0.03	0.16	0.22	0.32	0.44	0.65
0.85			0.14	0.19	0.29	0.42	0.62
0.86			0.11	0.17	0.26	0.39	0.59
0.87			0.08	0.14	0.24	0.36	0.57
0.88			0.06	0.11	0.21	0.34	0.54
0.89			0.03	0.09	0.18	0.31	0.51
0.90				0.06	0.16	0.28	0.48
0.91				0.03	0.13	0.25	0.46
0.92					0.10	0.22	0.43
0.93					0.07	0.19	0.40
0.94					0.03	0.16	0.36
0.95						0.13	0.33

Table 16
Causes of motor failure [43].

Causes of motor failure	Failure rate (%)
Overload (overheating)	25
Contamination	
Moisture	17
Oil and grease	20
Chemical	1
Chip and dust	5
Single phasing	10
Normal insulation	12
Deterioration	5
Other	5

due to the pipe work, ducting, insulation etc have been minimized or not.

9.4.2. Cleaning

A clean motor is more than just a pretty motor. Avoid too many thick coats of paint or dirt build-ups which can foul heat transfer surfaces. Dirt is a very general word that can mean many things: dust, corrosive builds up, sugary syrups from food processing, electro-conductive contaminants like salt deposits or coal dust. It can damage a motor in three ways. It can attack the electrical insulation by abrasion or absorption into the insulation. It can contaminate lubricants and destroy bearings. A clean motor runs cooler. Dirt builds up on the fan-cooled motor inlet openings and fan blades. This reduces the flow of air and increases the motor operating temperature. Dirt on the surface of the motor reduces heat transfer by convection and radiation. This is especially critical for totally enclosed motors since the entire cooling takes place on the outside surface. Heavily loaded motors are especially vulnerable to overheating, so they have little tolerance for dirt. Surface dirt can be removed by various means, depending upon its composition. Compressed air (30 psi maximum), vacuum cleaning and direct wipe down with rags or brushes are usually used. There has been a recent introduction of dry ice "sand" blasting to clean motor [47,119].

9.4.3. Lubrication

Many small or integral horsepower motors have factory-sealed bearings that do not require re-lubrication. All others require lubrication. One cannot merely be conservative and over-lubricate. There are many ways that improper lubrication shortens bearing life. Re-lubrication with different grease can cause bearing failure when two incompatible greases mix. Grease consists of oil in some type of constituent to give it body or thickness so that it does not run out of the bearing. Mixing greases with incompatible constituents can cause the components of the mixed grease to separate or harden. Adding too much grease or greasing too frequently can force grease past the bearing shield or seal into the motor, resulting in winding damage. Merely having too much grease in the bearing itself can prevent proper flow of the grease around the rollers. Sometimes bearing failures due to over-lubrication are interpreted as insufficient lubrication and intervals are made even shorter. Perhaps the worst problem with greasing is introduction of contaminants. Contamination occurs when strict cleanliness standards are not followed in grease storage and application. It may be wise to buy grease in more expensive individual cartridges rather than large quantities that are subject to contamination when refilling grease guns. Take special care with grease fittings. Clean the fitting before filling and keep the grease gun nozzle covered when not injecting grease [119]. Motors lubrication can save about 1–2% energy [47].

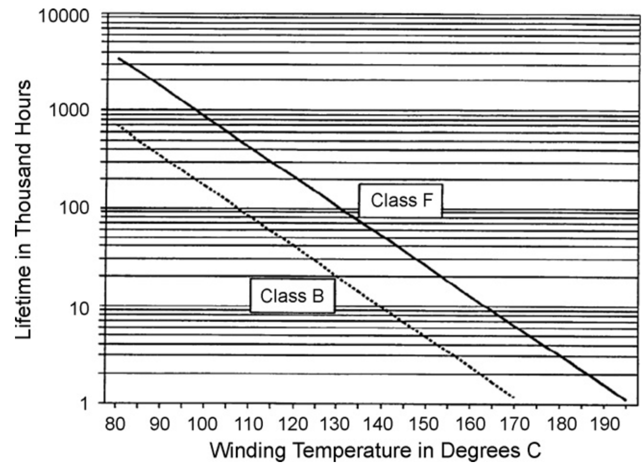

Fig. 17. Life vs. operating temperature for insulation systems [43].

9.4.4. Mounting, coupling, alignments

Maintenance issue, but if it is inadequate, it can result in serious maintenance problems. The entire structure must be rigid with a flat coplanar surface for the four mounting legs. The same applies to the structure for mounting the load. Both motor and load structure must be rigidly bound to the floor on a common structure. Failure to provide a solid mounting can lead to vibration or deflection which leads to bearing failure. Vertical motors can be even more demanding than horizontal motors because the mounting circle constitutes a small footprint for a large mass cantilevered above. Pliancy in the mounting structure can exacerbate low frequency vibration to which vertical motors are vulnerable.

Coupling alignment is often promoted for energy efficiency. Energy loss in couplings is sometimes overstated, but proper alignment is always important to bearing and coupling life. A slight misalignment can dramatically increase the lateral load on bearings. It can also shorten the life of the coupling. One source attributes 45–80% of bearing and seal failures to misalignment. Fig. 17 shows the life of motors with temperature [47,119].

9.4.5. Information and education

Publications and seminars are the main tools for distributing information. An important point is that the publications should be technically sound and always written with the target audience in mind. There are many different groups of people involved in the selection of a motor-driven system, from maintenance staff to accountants, and appropriate information has to be available for all of them. Another successful way of spreading information is through seminars. They should avoid being too general on the one hand and too academic on the other. An engineer who tells an energy saving story from real-life experience can bring the whole event to the level of the audience. In order to be able to present interesting case stories in publications and seminars, it is a good idea to set up demonstration and pilot projects that deal with specific problems. Involving equipment suppliers is also a good idea, both as speakers and exhibitors [111].

An energy guide label with details of energy savings feature in many countries found to be effective to raise the awareness among the users. Mass media can play an important role by disseminating useful energy savings information to the users so that users practice energy efficiency while they use and purchase energy-efficient equipment/machineries in replacing or buying new one.

9.4.6. Finance mechanisms

Rebates are a very simple way to encourage the sales of energy-efficient motor systems. The support of distributors is of vital

importance. They need to allocate enough space to stock high-efficiency systems. Distributors must have a financial incentive to participate and, even more importantly, they must believe in the effectiveness of the overall programme. One way of giving financial support is to make allowances on company taxes when investments are made in energy-efficient motor systems. The UK Enhanced Capital Allowances Scheme (ECA) is a good example of such a programme. Another type of financial support is leasing. This is usually offered by the manufacturer and, if necessary, supported in some way by government. It is principal attraction to customers is that they can achieve savings without having to spend capital. Contracting is usually offered for larger motor systems, such as compressed air systems. Some special contracts even specify that the customer pays the contracting company only from savings in energy costs. This is an excellent way of completely overcoming the barrier of capital shortage [111].

9.4.7. Energy savings using power optimizing devices

Various power optimizing devices which are essentially "black boxes" are available in the market. They generally contain electronic circuits that monitor parameters such as motor load and power factor and continuously adjust the power supply to the motor to minimize consumption. Tests with constant air volume AHUs, where fan speed cannot be modulated, showed that power optimizing devices are able to achieve energy savings. The actual savings achieved depend on the motor loading. For motors loaded to only 60–70% of the rated capacity, energy savings of over 20% was achieved [44].

10. Conclusion

From the review, it has been identified that energy audit is an effective tool that helps to collect data necessary for estimating motor energy use. It also helps to identify where energy waste is taking place so that necessary measures can be implemented.

This review also showed quantitatively different types of losses occurring in electric motors. It has been found that highest amount of loss (i.e. 58%) taking place at the rotor and stator parts of a motor [44,50,51]. It may be stated that this is the one potential area where loss can be reduced.

It was found that about 75% of motors are operated below 60% load [47]. In some cases it was found that motors are operated at 40% load. It was reported by many researchers that motors are efficient if they are operated above 75% of their load. So, there are huge potential to save energy and avoid indirect emission by proper sizing/selection of motors. VSDs are an option in such situations to match the required loads thus savings energy. However, it should be noted that VSDs are economical only for large motors [12]. Based on the discussions it has been found that motors are not used at full load and in most cases they are oversized that encourage wastage of energy. One of the best solution to overcome this problem is to use computer tools such as MotorMaster+, EuroDEEM, CanMOST and so on. It masy also be noted that energy can be saved using high-efficient motors instead of standard-efficient motors. Many researchers found use of efficient motors economically viable based on the estimation of payback period. So, energy-efficiency regulations (i.e. regulatory, voluntary, incentive based) in some cases play an important role in reducing energy consumption and environmental pollutions. However, appropraite test procedure must be developed to establish such regulations. As the global market is getting borderless, a harmonized test procedure will be more useful.

Along with the use of technology and regulations, proper maintenance should be ensured. Based on Table 16 [43], it has been found that major share of motor fails due to overheating (25%) and contamination (43%). Preventive maintenance will protect this type of failure and contamination. Awareness and education also important instruments those are very useful in energy savings. Mass media can play an important role by publicizing the benefits of energy savings. Apart from that an effective energy guide label should be developed based on consumer research survey and should be displayed on the products, sales centre and other appropriate places. This will encourage end users to buy more-efficient products.

This review paper could be useful for motor designers, operators, energy managers and motor manufacturers to fully understand energy saving opportunities in electric motors and further to take proper energy saving measures to enhance energy efficiency in buildings. They could help designers adopt proper design options and concepts in the decision-making process during the initial planning and design stages (i.e. how to reduce losses) and help operators to use advanced control algorithms in practical operations to reduce the global energy consumption in electric motors and enhance control stability and environmental sustainability. It could also be useful for the government to evaluate the current electric motor energy policies.

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